

IMPACT OF THE PHONON COUPLING ON THE DIPOLE STRENGTH AND RADIATIVE NEUTRON CAPTURE

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The E1 strength functions and radiative capture cross sections for several compound Sn isotopes, including unstable ¹³²Sn and ¹⁵⁰Sn, have been calculated using the self-consistent microscopic theory. In addition to the standard RPA or QRPA approaches, the method includes the quasiparticle-phonon coupling and the single-particle continuum. The results obtained show that the phonon contribution significantly affects the pygmy dipole resonance, which is of particular relevance for a proper description of the radiative neutron capture. The impact of the phonon coupling on the pygmy dipole resonance and the radiative neutron capture cross sections increases with the $(N - Z)$ difference. For example, in the (0-10) MeV interval the full theory gives 17% of the energy-weighted sum rule for ¹⁵⁰Sn and 2.8% for ¹²⁴Sn, whereas the continuum QRPA approach gives 5.1% and 1.7%, respectively. These results indicate the importance the self-consistent calculation can have, especially when applied to neutron-rich nuclei of astrophysical interest. The comparison with the widely-used phenomenological Generalized Lorentzian approach shows that the (Q)RPA approach gives an increase in the neutron capture cross section by a factor of 2 for ¹³²Sn and a factor of 10 for ¹⁵⁰Sn and that the inclusion of the phonon coupling still increases these cross sections even further, by a factor of 2–3.

KEYWORDS : Phonon Coupling, Radiative Neutron Capture Cross Sections

1. INTRODUCTION

Inclusion of the coupling of single-particle degrees of freedom with phonon degrees (in short, phonon coupling or PC), in addition to the standard Random Phase Approximation (RPA) for magic nuclei or the Quasi-particle RPA (QRPA) for non-magic nuclei, is a main line of the recent development of microscopic nuclear theory. In particular, the Extended Theory of Finite Fermi Systems (ETFFS) [1] includes both PC and the single-particle continuum, the latter being absolutely necessary for nuclei with the nucleon separation energy near zero. This approach has been recently generalized to include pairing in the quasiparticle time-blocking approximation [2], (ETFFS(QTBA)). This and other approaches developed with the PC have been supplemented with consideration of the self-consistency between the mean field and the effective interaction [3,4,5]. On this basis, it was possible to perform a transition from the two sets of parameters used (the first one for the effective force and the second one for the mean field) to one unique set based on Skyrme force. Both these improvements –the single-particle continuum and the self-consistency– are of great importance, for astrophysics as well as for nuclear data evaluations, since they provide a reliable framework to

calculate the structure of exotic nuclei, especially those with great neutron excess and/or with the nucleon separation energy close to zero.

The PC role in the description of giant resonances in stable nuclei is well known: it explains approximately 50% of the observed widths, their gross structure and sometimes even the fine structure [1]. However, the direct influence of the PC on giant resonances in unstable nuclei is less studied. It is clear that the PC role should be important for the widths here as well. But so far, the characteristics of the giant resonances in unstable nuclei have only been systematically studied within the (Q)RPA [6,7,8] approach.

The PC plays an important role in the determination of the so-called pygmy dipole resonance (PDR), which is the low-energy part of the giant dipole resonance (GDR) that can exhaust about 1 – 2% of the energy-weighted sum rule (EWSR). At present there is no clear understanding around some important questions related to PDRs, see [6,9]. This resonance is also known to be of particular relevance in the description of the radiative neutron capture [8,10]. However, the PDR has essentially been treated on the basis of phenomenological models up to now. The question arises for exotic nuclei where the phenomenological approach may fail because of the specific features of the PDR in such

nuclei [6,8]. The answer is the same as for the problem of giant resonances in unstable nuclei and is quite obvious: it is necessary to use a reliable theory for such nuclei, i. e., as discussed above, a self-consistent theory which accounts for the PC and the single-particle continuum in addition to the standard (Q)RPA.

In our previous works [4,9,11] we developed the self-consistent version of the ETFFS(QTBA) using a discretization procedure for the single-particle continuum with different kinds of Skyrme forces, including SLy4, where the velocity-dependent parts of forces were considered in the local approximation (we called it DTBA). The consequence of such a simplification is the necessity to renormalize the interaction in order to obtain the spurious state at zero energy.

The main goals of the present work are: i) to study the PDR and GDR consistently in stable ^{124}Sn and unstable ^{132}Sn , ^{150}Sn isotopes using the variant (DTBA) of the microscopic self-consistent version of the ETFFS; ii) to investigate the impact of the PC on the radiative neutron capture cross section.

2. SELF-CONSISTENT CALCULATIONS OF THE PDR AND GDR

We use the SLy4 Skyrme force [12] which proves to be rather successful in description of ground states and some excited states within the (Q)RPA. The ground states are calculated within the Hartree-Fock-Bogolyubov approach using the HFBRAD code [13]. The residual interaction for the (Q)RPA and the following QTBA calculations is derived as the second derivative of the Skyrme functional (see details in [4]).

Fig. 1 shows the photoabsorption cross sections for ^{124}Sn and ^{150}Sn nuclei. A more detailed discussion on ^{132}Sn can be found in [11]. One can see that the phonon contribution is noticeable for the PDR and it is increased with the (N-Z) difference growth. For example, in the (0-10) MeV interval the full theory gives 17% of EWSR for ^{150}Sn and 2.8% for ^{124}Sn , whereas within the QRPA approach we have 5.1% and 1.7%, respectively.

Fig. 2 shows the comparison of the E1 strength functions obtained in the framework of our self-consistent DTBA version with the (Q)RPA calculations. We used a normalization procedure here. Namely, the DTBA strength has been folded with a Lorentzian of 1 MeV width for DTBA and 2.7 MeV for RPA in order to broaden the GDR to a typical width of 4 MeV, as observed experimentally for the stable nuclei. Although the DTBA peak energy of ^{132}Sn is predicted at a relatively low energy (13.5 MeV) with respect to experimental data (16.1 MeV), the PDR is correctly reproduced around 9.8 MeV [14].

In Fig. 2, our results are also compared with those obtained with the phenomenological Generalized Lorentzian strength function [15]. The Lorentzian approach is widely used for practical application, though it suffers from shortcomings of various sorts. On the one hand, the location of

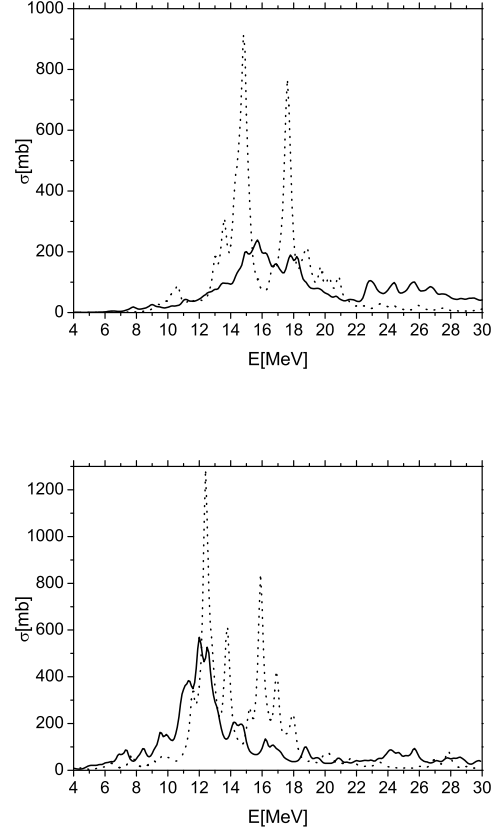


Fig. 1. Photoabsorption cross sections for ^{124}Sn (top) and ^{150}Sn (bottom) calculated within the self-consistent ETFFS(DTBA) without (dotted curves) and with (solid curves) the PC.

the GDR maximum energy and width remain to be predicted from some underlying model for each nucleus. For many applications, these properties have often been obtained from a droplet-type of model or from experimental systematics [10]. In addition, the Lorentzian model is unable to predict the E1 strength at energies below the neutron separation energy. Different parametrizations or functional forms (including in particular an energy- and temperature-dependent width) have been proposed (see e.g. [15]) to reconcile experimental data in the photon or radiative neutron capture channels, but none of the proposed closed forms can nowadays explain the various trends observed at low energies. Most of all the Lorentzian approach cannot provide any predictions on the low-energy PDR, neither on its presence, nor on its characteristics. For this reason, it is of particular interest to analyze to what extent our predictions based on self-consistent microscopic models differ from those used in practical applications. One can see that the difference between [15], on the one hand, and both the QRPA and DTBA, on the other hand, increases with the (N - Z) difference. As our preliminary calculations have shown, the main reason is that the A-dependence of the integral

characteristics of neutron-rich nuclei differs strongly from the usual ones. This fact demonstrates the non-applicability of the standard systematics (e.g. $E_0 = 80A^{-1/3}$) for unstable nuclei.

3. CALCULATIONS OF RADIATIVE NEUTRON CAPTURE CROSS SECTIONS

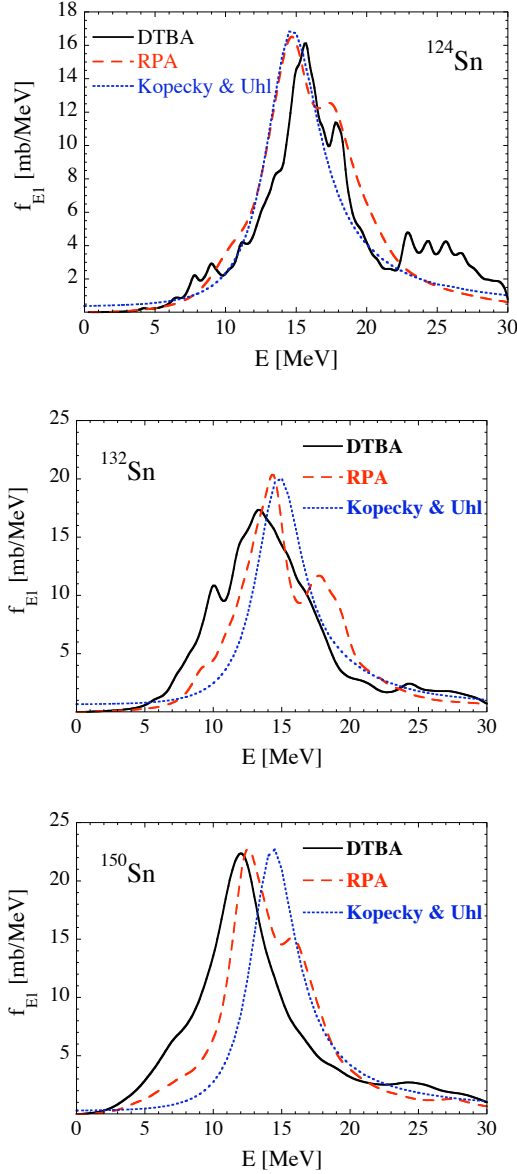


Fig. 2. Strength functions for the isovector 1^- states in ^{124}Sn , ^{132}Sn and ^{150}Sn nuclei. The solid, dashed and dotted curves are for the DTBA, (Q)RPA and Kopecky-Uhl [10, 15] approaches, respectively

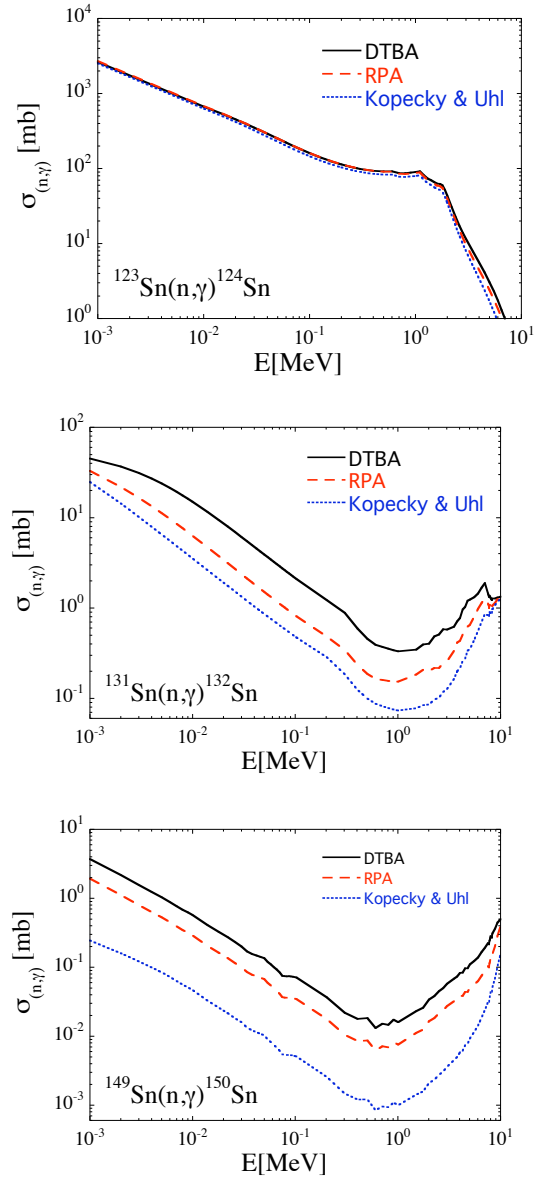


Fig. 3. Radiative neutron capture cross sections obtained with the γ -ray strength functions of ^{124}Sn , ^{132}Sn , ^{150}Sn shown in Fig. 2

The radiative neutron capture cross sections have been calculated using the reaction code TALYS [16]. The DTBA strength functions with and without PC have been included in the calculation of the electromagnetic de-excitation transmission coefficients. The final radiative neutron capture cross sections calculated with the strength functions of Fig. 2 are shown in Fig. 3. We show the cross sections leading to the ^{124}Sn , ^{132}Sn and ^{150}Sn compound nuclei, respectively. Note that such reactions are of interest for the r-process nucleosynthesis, and illustrate the impact that the low-lying strength can have on cross sections, and consequently on reaction rates. As seen in Fig. 3, including the PC increases the cross section by a factor of 2–3. In

all cases the trend is clear: the cross sections follow on the whole the strength functions shown in Fig. 2, and the DTBA with an extra low-lying strength gives a final reaction cross section (and Maxwellian-averaged rate around $T = 1 - 2 \cdot 10^9 K$) about 3 times larger compared with the prediction obtained with the HFB+QRPA calculation [7]. For the case of the compound ^{124}Sn , we see in Fig.2 that the difference between the DTBA and QRPA strength functions is much smaller than for ^{132}Sn and ^{150}Sn . It is necessary also to note here that the theoretical consideration for ^{124}Sn is based in a sense on the known experiment, this is especially true for the Kopecky-Uhl approach (see below). For these reasons, the appropriate cross sections in Fig.3 are insensitive by sight to the three strength functions.

In Fig. 3 we also compare the cross sections with the widely used Generalized Lorentzian strength function [10, 15]. We have found that for the stable ^{124}Sn nucleus the cross section is almost identical to the one obtained with the ETFFS approach, although the strength functions can differ significantly at energies below the neutron separation energy. For neutron-rich isotopes, the QRPA strength gives a significant increase in the cross sections with respect to those obtained with the Lorentzian function of [15], namely by a factor of 2 for ^{132}Sn and a factor of 10 for ^{150}Sn . This confirms the results of [7]. Moreover, the inclusion of PC increases the cross sections for the unstable ^{132}Sn and ^{150}Sn by a factor of 2–3 at the energies around 100 keV, as illustrated in Fig. 3. These results demonstrate the necessity of self-consistent approaches for the calculation of the radiative capture cross sections of exotic neutron-rich nuclei.

4. CONCLUSION

The electric dipole strength function has been calculated on the basis of the ETFF(DTBA) model which simultaneously takes into account the RPA or QRPA configurations, the more complex $1p1h \otimes \text{phonon}$ configurations and the single-particle continuum. These are the necessary ingredients for a consistent study of the giant and pygmy resonances.

It was demonstrated that the DTBA approach predicts a relatively large low-lying strength compared to the (Q)RPA one around 10 MeV in the neutron-rich Sn isotopes. The radiative neutron capture cross sections were calculated with the DTBA and (Q)RPA strength functions and shown to be sensitive to the predicted low-lying strength. In particular, the calculations demonstrated that including the PC leads to a significant increase in the reaction cross section. The comparison with the Generalized Lorentzian approach confirmed the non-applicability of the phenomenological approaches for neutron-rich nuclei.

The ETFFS(DTBA) approach is believed to provide a more complete and coherent description of the gamma-ray strength function than the previous models used so far. For astrophysics applications in particular, such calculations are highly recommended for a more reliable estimate of the electromagnetic properties of exotic nuclei.

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